

NATURE AND ORIGIN OF EXOTIC-RICH DRIFT IN THE APPALACHIAN PLATEAU

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ABSTRACT. The differentiation of drift in the Appalachian Plateau into two facies, a valley facies rich in exotic rock types and an upland facies poor in exotic rock types, is an intriguing phenomenon not encountered in the mid-continent region. The composition of stratified drift in valleys of the Plateau is dependent on two factors: (1) distance from source outcrops of different rock types, and (2) distance of fluvial transportation in meltwater streams prior to deposition. Exotic rock types are generally more resistant than local rock types in the fluvial environment, so that outwash gravels contain more exotics than ice-contact deposits, which in turn contain more exotics than nearby till. Exotic-rich drift found in main valleys of the Plateau has been created by multicyclic reworking of exotic-rich stratified drift during repeated glaciation. On the basis of the distribution of various exotic rock types in drift, the concept of extrusion ice flow in the main valleys of the Plateau and the idea of an Adirondack outflow center must be questioned.

INTRODUCTION

The separation of drift in the Appalachian Plateau of central New York and northernmost Pennsylvania into two facies, an exotic-rich valley facies and an exotic-poor upland facies, is an intriguing phenomenon not encountered in the mid-continent region. At least three theories have been proposed over the years to account for this situation. These theories will be reviewed, and new evidence to test these theories will be presented in this report.

Regional bedrock geology.—Southcentral New York and northeastern Pennsylvania are included in the Appalachian Plateau, whose northern margin is marked by outcrops of Lower and Middle Devonian limestones (fig. 1). These limestones include the Helderberg Group and Onondaga Limestone, which are mostly massive limestones as much as a few hundred meters thick. They form a prominent escarpment more than 300 m high around much of the Plateau. The Onondaga Limestone is notably cherty. A minor limestone only a few meters thick, the Tully Limestone, occurs at the top of the Middle Devonian sequence in the Finger Lakes region. The remainder of the Appalachian Plateau south of the limestone outcrops in this region is underlain by a thick sequence of very gently folded Upper Devonian shales, siltstones, and sandstones.

To the north of the Appalachian Plateau, a variety of Lower Paleozoic sedimentary rock types crops out in the Ontario-Mohawk lowland. Included are red, green, yellow, and white quartzose sandstones of the Medina and Lorraine Groups and hematite of the Clinton Group. Still farther to the north, crystalline rocks crop out in the Adirondack Mountains of northern New York and in the Canadian Shield. The high peaks of the Adirondacks rise to over 1500 m in altitude and are composed of anorthosite. The rest of the Adirondacks and nearby Canadian Shield are composed of a variety of igneous and high-grade metamorphic rocks.

Glaciation of the Appalachian Plateau.—There is good evidence preserved for a least three glaciations of the Appalachian Plateau in southcentral New York and northeastern Pennsylvania, first during Illinoian time, again during Early Wisconsin time, and finally during Late Wisconsin time (Sevon, Crowl, and Berg, 1975; Coates, 1976). The Late Wisconsin deglaciation, which was in full progress somewhat before 13,000 b.p., was interrupted by a short-lived readvance that deposited the Valley Heads moraine (Krall, 1977).

Glacial deposits in the Appalachian Plateau vary greatly depending on their topographic setting and the nature of local bedrock. Drift in upland areas consists mostly of till with minor amounts of stratified deposits. This drift is nearly devoid of exotic rock fragments such as: chert, limestone, quartzose sandstone, and crystalline rocks. Exotics commonly make up less than 1 percent of pebble-sized stones in upland till in Pennsylvania and only 1 to 5 percent in southcentral New York (Aber, ms, 1976). Thus, upland till is composed largely of local bedrock material.

In contrast, drift in the main valleys of the Plateau contains abundant exotics. This drift is mostly stratified gravel, sand, and silt deposits with minor amounts of till. As much as 50 percent of some gravel deposits in valleys of southern New York is made up of exotic stones (Randall,

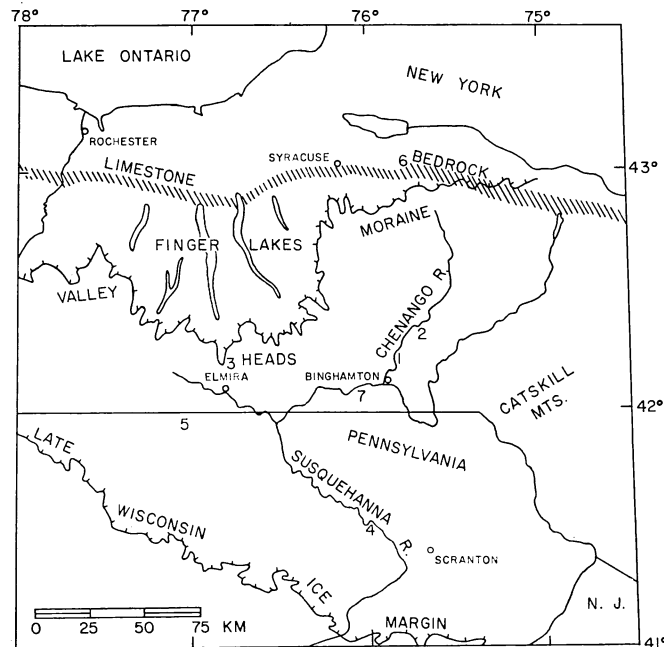


Fig. 1. Map of study region of central New York and northeastern Pennsylvania showing geologic and drainage features. Numbers indicate localities discussed in text: (1) Chenango Valley State Park sequence, (2) Brisben esker system, (3) Valley Heads moraine at Horseheads, (4) terraces at West Falls, (5) terraces at Tioga Junction, (6) Oneida-Hamilton area till, (7) stratigraphy at Vestal near Pierce Hill.

1978). The exotic-rich drift is confined to low elevations in or adjacent to "through valleys" which connect with the Ontario-Mohawk lowland to the north (Moss and Ritter, 1962). The so-called through valleys, results of both glacial and fluvial erosion (Coates, 1974), are major north-south bedrock valleys which continue across the drainage divide formed by the Valley Heads moraine. All the Finger Lakes, as well as the Chenango, parts of the Susquehanna, and other rivers occupy through valleys, which contain exotic-rich drift.

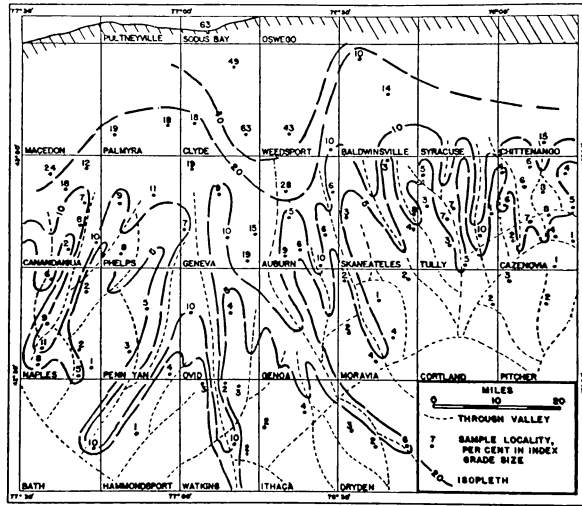
Theories concerning exotic-rich drift.—At least three theories have been proposed to account for the unusual distribution of exotics in drift of the Plateau. MacClintock and Apfel (1944) proposed that exotic-poor drift was deposited by an earlier glaciation they called "Olean" and that exotic-rich drift was deposited by a later glaciation they called "Binghamton." Later studies have shown that exotic-rich and exotic-poor drift are of the same age, and both were deposited during the Late Wisconsin glaciation (Denny and Lyford, 1963). Coates (1963) has called the Binghamton drift an exotic-rich, through-valley facies of the Olean.

Holmes (ms and 1952) developed a mechanism for the distribution of exotics based on the theory of "extrusion flow" in ice sheets. He documented the great concentration of exotics in till within the Finger Lakes valleys (fig. 2A, B, C) and concluded that the distribution of limestone and red and green sandstone pebbles shows that, ". . . southward transportation was much more effective along the through-valleys than along the intervening uplands. This is quite in keeping with the interpretation that the valleys themselves were formed by vigorously eroding basal ice currents moving by extrusion flow . . ." (1952, p. 1003). Holmes assumed that crystalline exotics, which are not concentrated in drift within the valleys, might have been derived largely from earlier drift of unknown distribution.

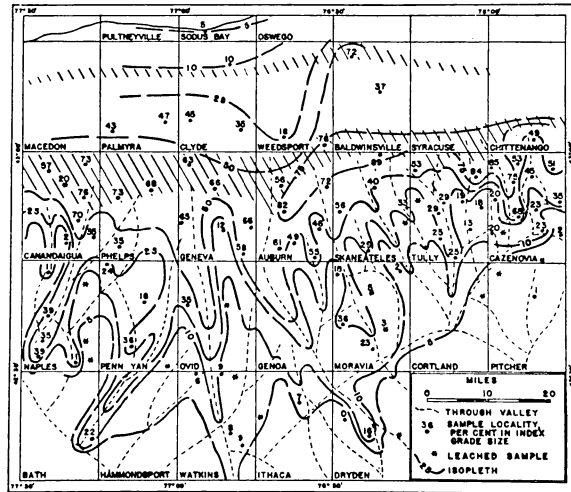
Demorest (1942, 1943) conceived the theory of extrusion ice flow, which he contrasted with "gravity flow." He suggested basal portions of an ice sheet could flow (or extrude) more rapidly than higher portions of the ice sheet due to increased plasticity of ice under pressure. The idea of extrusion flow has been rejected by nearly all modern glaciologists (Embleton and King, 1968), but given the special topography of the Appalachian Plateau, perhaps it did occur in the deep troughs of the Finger Lakes.

Another mechanism, which has been proposed to explain the distribution of exotics, involves reworking of exotics within through valleys. Outwash gravel deposits of Late Wisconsin age preserved in valleys of the Plateau today are usually high in exotic-stone content. Denny (1956) hypothesized that similar exotic-rich gravels were present in front of the advancing Late Wisconsin glacier. The Late Wisconsin glacier may have scooped up the gravels and redeposited those exotics in till at low elevations near the through valleys, but the glacier was unable to move exotics out of the valleys onto the higher uplands. Support for this mechanism has been provided by J. Flint (ms), who

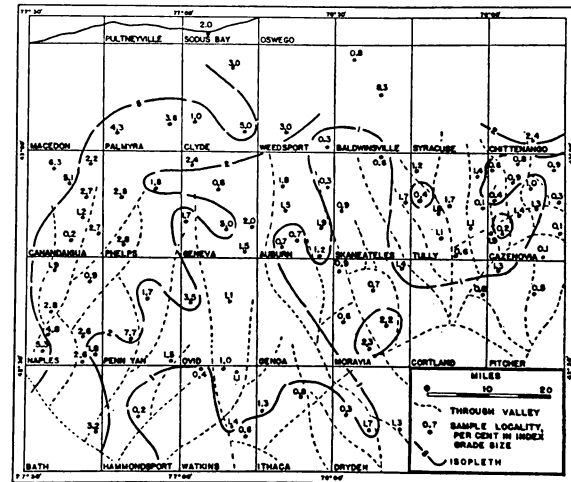
A.



B.



C.



found a high proportion of well-rounded exotics in till immediately south of the Susquehanna River valley in the Binghamton-Elmira area. He concluded, that these exotics were derived from gravel deposits in the Susquehanna valley and "plastered" onto low areas south of the valley by the Late Wisconsin glacier.

Method of study.—The variation in exotic-stone content of drift was investigated for this study by use of pebble counts and shape measurements. Hundreds of samples of gravel-sized material were collected from natural and man-made exposures of stratified drift and till in selected areas throughout the Plateau. Both composite samples from several beds within exposures and samples from particular, distinctive beds were collected. Multiple samples were collected from different portions of large exposures. Samples containing approx 200 pebbles each were used for rock counts. The number of each rock type present was counted and composition percentages were calculated for each sample. Initially, three size grades were counted: 50 to 25 mm, 25 to 13 mm, and 13 to 6 mm. However, little difference in composition was found between these size grades, and so the 25 to 13 mm size, which was the most convenient to work with, was selected for use throughout this study.

Pebble shape measurements were made using the Cailleux roundness measure, which is calculated using the formula:

$$\frac{2 R}{A} \times 1000$$

where R is the minimum radius of curvature of the stone in the principal plane, and A is the long axis of the stone (Embleton and King, 1968). Both R and A may be readily measured using a template of graduated circles. Using this roundness measure, a sphere has a roundness of 1000, while a cube has a roundness of zero. Shape measurements were performed on limestone (limestone herein refers to limestone plus dolomite, not differentiated) and gray sandstone pebbles, which are generally the most abundant and durable rock types in the drift. Whenever possible, samples of 50 pebbles of each rock type were measured. Pebbles of shale and other rock types, which are either non-durable or not abundant, were not used for this shape measurement. As another measure of stone shape, the percentage of all pebbles (except shale) with concave surface areas was counted for some samples.

EXOTIC-RICH STRATIFIED DRIFT

Stratified drift within major valleys of the Appalachian Plateau occurs in a variety of landforms including kames, eskers, kame terraces,

← Fig. 2. Maps of distributions of rock types (small pebble size) in till of the Finger Lakes region: (A) red plus green sandstone, (B) limestone plus dolomite, (C) crystalline types. Generalized outcrop areas of source bedrock shown in each case by diagonal lining. Note the concentration of red and green sandstone and limestone in till along through valleys. Crystalline exotics are not concentrated in through valleys; their abundance decreases from northwest to southeast. Taken from Holmes (1952, p. 1002-1004).

irregular valley plugs, and outwash terraces. These landforms and deposits have been best interpreted using the "morphologic sequence" concept (Koteff, 1974). A morphologic sequence refers to the downstream progression of meltwater deposits and landforms associated with a particular ice margin position (fig. 3).

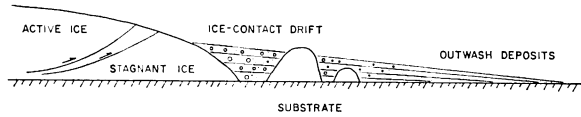


Fig. 3. Profile through a typical fluvial/ice-contact sequence of meltwater deposits. Meltwater and rock debris are supplied by active ice, while isolated ice blocks represent sites of future kettle holes. The graded nature of the sequence as well as the general downstream decrease in sediment size and increase in sediment sorting are indicated schematically. Adapted from Koteff (1974, p. 128).

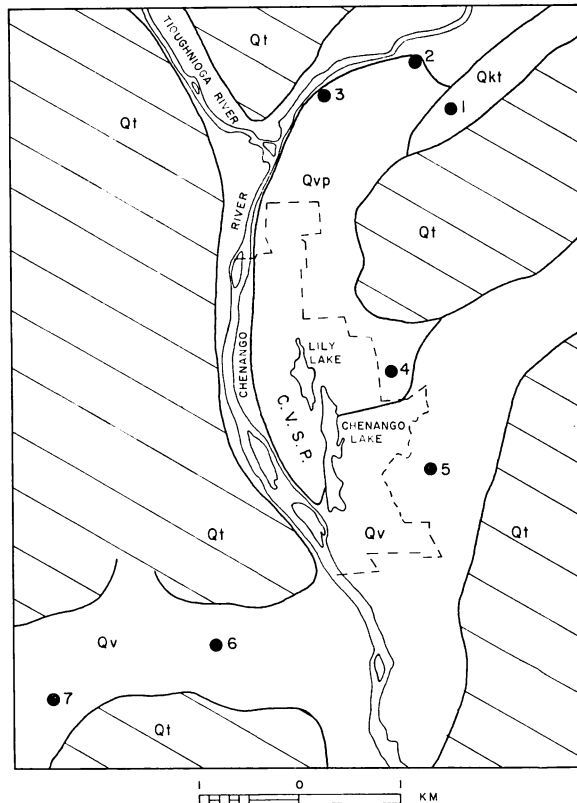


Fig. 4. Map of Chenango Valley State Park area (Chenango Forks 7½-minute quad) showing Quaternary geology: Qkt = ice-contact kame terrace, Qvp = ice-contact valley plug, Qv = outwash deposits, Qt = bedrock uplands mantled by till. This graded sequence of ice-contact and outwash deposits was laid down immediately south of a still-stand position of an ice tongue in the Chenango River valley. Lily and Chenango Lakes occupy kettle holes, where isolated ice blocks were located during deposition of this sequence. Sample sites 1 to 7 are shown, and sample site 8 is 3 km off the map to the south. Quaternary geology from Cadwell (ms).

The study of stratified drift using the sequence concept combined with numerous pebble counts and shape measurements demonstrates that there are definite downstream changes in the nature of stratified drift deposits. In a downstream direction, deposits forming sequences display an increase in sorting, stratification, and rounding of pebbles, and a parallel increase in exotic-pebble content (Aber, ms, 1978). Thus, ice-contact drift typically has a lower content of exotic stones, whereas outwash gravels have a higher content of exotic stones. These relationships may be readily demonstrated in many areas of the Plateau.

Chenango Valley State Park sequence.—Just north of Binghamton, a sequence consisting of an ice-contact valley plug and associated deltaic and outwash deposits is well preserved in the Chenango River valley (fig. 1). The pitted valley plug at Chenango Valley State Park (fig. 4) is made up of drift, which was deposited around and over stagnant blocks of ice that lay just south of an active ice margin (Cadwell, ms). Drift in this area is poorly stratified, contains many angular shale clasts, and has few exotics. This drift grades southward into high terraces, which consist of sandy deltaic beds, capped by topset gravel beds deposited by

TABLE 1
Sample data (13-25 mm size) from stratified drift of the Chenango Valley State Park sequence. Sample sites shown in figure 4

samp site	samp size	% shale siltst	% gray ss	% lime-stone	% chert	% qtz ss	% cryst	% other	% total exot		shape gray ss	no.
1	113	26.5	63.7	2.7	0.9	4.4	1.8	-	9.8		253	20
1	214	4.7	89.7	2.8	0.5	1.4	0.9	-	5.6		221	50
2	115	27.0	73.0	-	-	-	-	-	-		226	20
2	251	20.9	72.5	2.4	-	2.0	2.0	0.4	6.6		210	50
3	124	28.2	62.9	2.4	0.8	3.2	2.4	-	8.9		228	20
3	76	28.8	60.3	1.4	1.4	5.5	1.4	1.4	10.9		290	20
4	117	17.9	72.6	4.3	-	4.3	0.9	-	9.5		309	20
4	104	26.0	60.6	9.6	-	2.9	1.0	-	13.4		382	20
5	117	13.7	72.6	6.8	1.7	3.4	1.8	-	13.7		330	20
5	110	10.0	60.9	20.9	-	3.6	4.5	-	29.1		248	20
5	87	21.8	54.0	11.5	2.3	5.7	4.5	-	24.2		380	20
5	240	3.8	75.8	8.3	1.7	8.8	1.7	-	20.4		356	50
6	238	9.7	66.8	11.3	1.8	8.0	2.6	-	23.5		364	50
7	119	7.6	71.4	10.1	2.5	5.0	3.4	-	21.0		354	20
7	133	15.8	52.6	18.1	2.3	5.3	4.6	1.5	31.6		346	20
8	133	24.8	49.6	14.3	2.3	7.6	1.5	-	25.6		407	20
8	272	6.6	64.7	15.4	2.2	7.8	3.3	-	28.7		418	50

braided streams. These gravel beds are sorted and stratified. They contain rounded stones, little shale, and abundant exotics.

Multiple samples of gravel were collected and analyzed from eight exposures along this sequence (fig. 4 and table 1). In a downstream direction, there is a substantial, although somewhat variable, increase in abundance of exotic pebbles and pebble roundness (fig. 5A, B). Ice-contact portions of the sequence (sample loc 1-4) are exotic-poor, whereas outwash portions of the sequence (sample loc 5-8) are exotic-rich. The downstream increase of exotic pebbles along this sequence is due to greater percentages of limestone, chert, and quartzose sandstone, which are the most abundant exotics present. All three of these lithologies are substantially more durable during fluvial transportation than the locally derived gray shale, siltstone, and sandstone; the local rocks are all subject to splitting along parting planes. Hence, the more durable exotic stones were concentrated by fluvial action and are more abundant in those deposits that were laid down after longer distances of meltwater transportation. Crystalline exotics seem to be an exception to this situation, as the amount of crystalline exotics neither increases nor decreases much along the sequence (table 1). There is a great variety of crystalline rock types in stratified drift, ranging from quartzites to micaceous gneisses and schists, and some types are much more durable than others in the fluvial environment. This fact may explain why crystalline exotics as a group do not follow the trends of the other exotics.

Middle Chenango River valley.—Along the Chenango River valley north of Chenango Valley State Park, between the towns of Greene and Norwich, a complicated mosaic of stratified drift forms is preserved (Cadwell, ms). Many of the individual drift deposits cannot be correlated with a specific ice-marginal position. There is, however, a good relationship between drift composition and meltwater transportation. The effects of meltwater transportation on the stratified deposits can be estimated by the roundness of locally derived clasts (gray sandstone). Deposits in this area with high roundness values indicative of long fluvial transportation usually contain high percentages of exotics, whereas deposits with lower roundness values usually contain fewer exotics (fig. 6A). Certainly, the depositional environment adjacent to an ice sheet is subject to daily and seasonal variations, so the degree of scatter shown by the data from this area is not unexpected. The higher percentages of exotics in samples with high roundness values is due to greater amounts of limestone, chert, and quartzose sandstone. Crystalline exotics do not follow this pattern (fig. 6B). The total percentage of crystalline pebbles seems not to have been greatly affected by meltwater transportation.

On the basis of drift composition, water-well data, and fresh exposures, the depositional history of the Brisben esker system (fig. 1) may be reconstructed in some detail. The Brisben esker system (fig. 7) comprises several linear segments preserved at two elevation levels. Low-level segments are found in the main valley of the Chenango River, and a

higher abandoned valley (Wheeler Brook valley) contains a high-level segment of the esker. The higher esker segment is the "downstream" end of the esker system, while lower segments in the main valley are "upstream" portions of the system. A complete transverse exposure of one end of a low-level segment reveals that the esker at that point is composed of a core of bouldery-gravel lenses which grade laterally into well-sorted gravel beds near the esker flanks. The bouldery-gravel lenses are similar to the sliding-bed facies of esker gravels that Houston (1977) has described, and they are evidence for esker deposition within a subglacial tunnel. A thin cover of ablation till also indicates that the esker was deposited in a subglacial tunnel. The subsurface structure of the low-level esker segments is revealed by water-well data (C. McClean, water-well driller of Greene, N. Y., 1976, personal commun.). At least

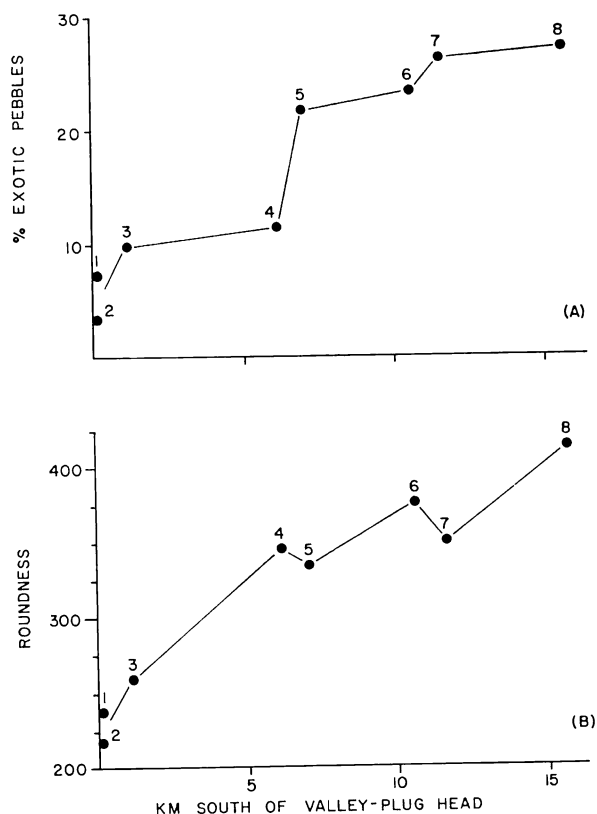


Fig. 5. Variation of sediment (13-25 mm size) characteristics along the Chenango Valley State Park sequence: (A) percentage of exotic pebbles, (B) Cailleux roundness measure of gray sandstone pebbles. The plotted points represent mean values of multiple samples taken from 8 sample sites (fig. 4 and table 1). Note the general downstream increase in both exotic-pebble content and pebble roundness along this sequence.

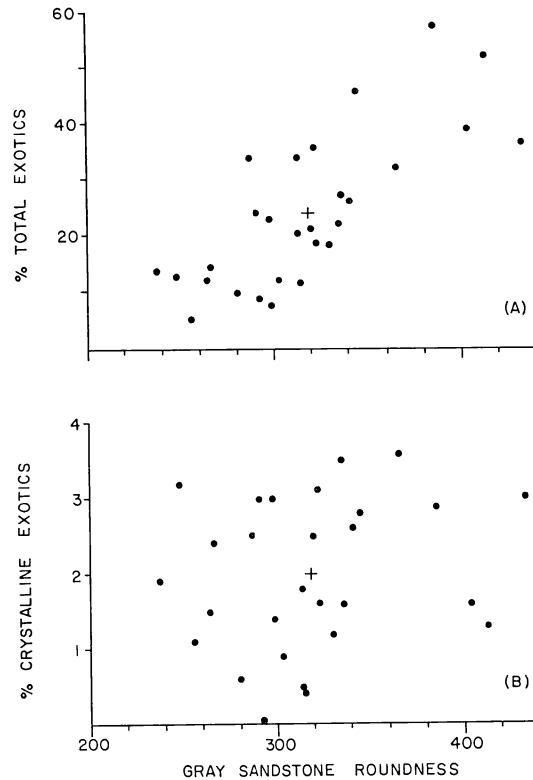


Fig. 6. Plot of composition versus pebble roundness of stratified drift samples (13-25 mm size) from sites along the middle Chenango River valley between the towns of Greene and Norwich. Samples with high roundness values also have high percentages of total exotics (A), but the percentages of only crystalline exotics do not seem to be related to pebble roundness (B). Mean values for samples shown with crosses.

60 m of drift is present in the Chenango River valley in this area, and it appears that the lower 15 m, or more, of the esker has been buried by later outwash deposits (figs. 7 and 8).

The most surprising discovery concerning the Brisben esker is the great difference in composition between high-level and low-level segments of the system. The high-level esker segment contains only 12.3 percent (2/443, $s = <0.1$ percent)¹ exotic pebbles, and gray sandstone roundness is low at only 284 (2/90, $s = 20$), whereas the low-level segment contains 19.7 percent (2/459, $s = 0.2$ percent) exotic pebbles, and gray sandstone roundness is somewhat higher at 321 (2/80, $s = 8$). Since exotics are generally more abundant in downstream portions of sequences, it seems anomalous that exotics are most abundant in the "upstream"

¹The number of samples/total number of pebbles in samples used to calculate percentages and the standard deviation (s) about the mean are shown in parentheses.

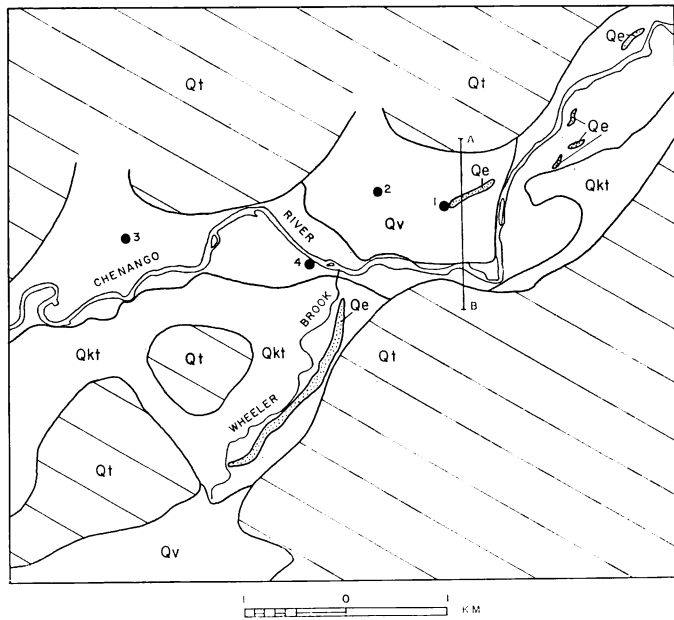


Fig. 7. Map of Chenango River valley and vicinity (Brisben 7½-minute quad) showing segments of the Brisben esker system (Qe). The large esker segment in Wheeler Brook valley is the “downstream” end of the system, and segments in the Chenango River valley are “upstream” portions. The positions of four water wells are shown by dots as well as the position of cross section A-B, which appears in figure 8. Exposure of esker discussed in text is located beside water well 1. Quaternary geology from Cadwell (ms).

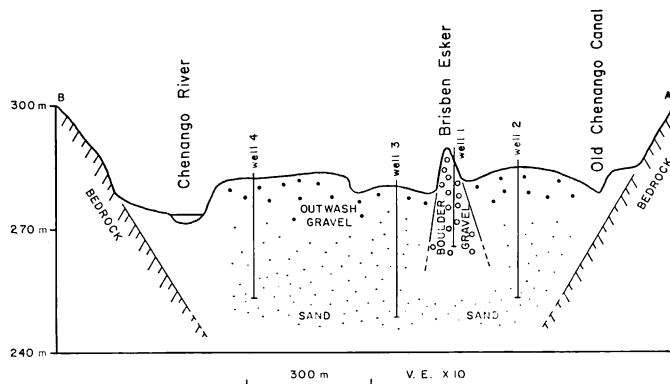


Fig. 8. Cross section (A-B) through Brisben esker segment. Water wells shown in figure 7 are projected onto the section; wells 2 to 4 are all finished in sand, while well 1 is finished in bouldery gravel (C. McClean, 1976, personal commun.). Well-sorted pebble and cobble outwash gravels up to 10 m thick surround the esker segment at the surface. Maximum depth of the bedrock valley here probably exceeds 60 m.

portions of the esker system. However, many eskers are known to be time transgressive with downstream portions being oldest, while upstream portions were deposited later as the subglacial drainage system extended itself headward (Banerjee and McDonald, 1975). During deposition of the Brisben esker system, the active-ice margin might have been retreating northward, away from the site of esker deposition beneath stagnant ice. Older, downstream portions of the esker system contain drift that was transported only short distances from the active-ice margin. Younger, upstream portions of the esker are composed of drift transported farther in subglacial streams from more distant active-ice positions. Thus, exotic rock types are more abundant in the younger, upstream portions of the esker system.

Total Chenango River valley.—The Chenango River lies in a through valley, which begins at the limestone belt at the northern margin of the Plateau and extends southward and southwestward to the

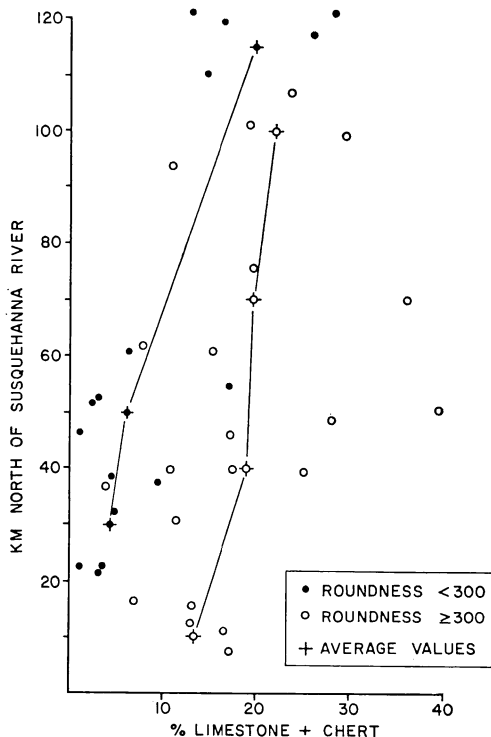


Fig. 9. Variation of stratified drift composition (13-25 mm size) along the Chenango River valley. Values are plotted according to their gray sandstone roundness. Both the Valley Heads moraine and the Onondaga Limestone are located at km 118. Average values for sites in 20-km segments of the valley are given. There is a general decrease in limestone content of stratified drift south of the limestone outcrops. However, samples with higher roundness values usually have more limestone than nearby samples with lower roundness values.

Susquehanna River (fig. 1). South of the area of limestone outcrop, a decrease in the amount of limestone present in stratified drift is expectable. Although a general southward decrease in limestone content does occur, the situation is not quite so simple (fig. 9). In most cases, drift containing pebbles with high roundness values contains considerably more limestone (and chert) than nearby drift with more angular pebbles. In fact, some outwash deposits in the middle and lower Chenango River valley contain more limestone exotics than ice-contact drift in the northern part of the valley near limestone bedrock. The composition of stratified drift along the Chenango valley was determined by two factors: (1) distance from source areas of different rock types, and (2) distance drift material was transported by meltwater streams. In any particular area, the meltwater transportation factor was the more important.

Valley Heads moraine at Horseheads.—One of the largest valley segments of the Valley Heads moraine is located in the Seneca Lake valley near Horseheads, N. Y. (loc. 3, figs. 1 and 11). These thick moraine deposits grade southward into outwash deposits, which can be traced along the Chemung River valley to northern Pennsylvania (Coates, Landry, and Lipe, 1971). The deposits making up the moraine are quite variable, ranging from till composed mostly of shale fragments to well-stratified sand and gravels with numerous exotics; exotic pebbles make up an average 22.2 percent (11/2083, $s = 15.3$ percent) of samples taken from the moraine. The high standard deviation of the sample data reflects the variability of the deposits. In contrast, outwash deposits graded to the moraine are less variable in composition and generally contain more exotics, the average value being 30.2 percent (6/1282, $s = 8.0$ percent). Likewise, there is an increase in gray sandstone pebble-roundness from the moraine (302, 11/155, $s = 59$) to outwash (384, 6/183, $s = 65$) deposits. The more uniform characteristics of the outwash deposits are a result of sediment sorting action, which took place in meltwater streams flowing away from the ice-marginal area near the moraine.

Northern Pennsylvania.—Upland drift in northern Pennsylvania includes only 1 to 2 percent, or less, exotic material, while exotics are fairly common in stratified drift. Along the Susquehanna River at West Falls (fig. 1), there are two, areally-extensive, high terraces consisting of stratified drift. Exotics are common in this drift, with recognizable exotics comprising 4.9 percent (4/813, $s = 0.4$ percent) of the pebble-sized fraction. Red sandstone is a common local bedrock type in this area, though, and it is impossible to tell exotic red sandstone derived from the Lake Ontario lowland from local red sandstone. If exotic red sandstone could be distinguished from local red sandstone, then the total exotic-pebble content of this drift might be 7 to 8 percent. Farther west in Pennsylvania, ice-contact drift forming terraces is found in the Tioga River valley. Terraces near Tioga Junction (fig. 1) contain 4.2 percent (3/821, $s = 2.7$ percent) exotics, including red sandstone, which does not occur locally. Certainly, fewer exotics occur in stratified drift

in northern Pennsylvania than in New York; but then, the major source beds for exotics are more than 95 km north of Pennsylvania.

General findings concerning stratified drift.—The relative durability in the fluvial environment of the various rock types is the key to understanding compositional variation of stratified drift in the Appalachian Plateau. Durable rock types, such as quartzite, quartzose sandstone, and most other exotic types, are more abundant in outwash deposits that were subjected to long distances of fluvial transportation and are thus well sorted and stratified and contain rounded stones. Less durable rock types, such as shale and micaceous crystalline rocks on the other hand, are more abundant in ice-contact deposits. This situation is common in many glaciated regions, for example in Denmark, where resistant lithologies such as crystalline rocks, coral limestone, and chert are concentrated in glaciofluvial gravels (Hansen, 1965). On the basis of these observations, the rock types common in stratified drift of the Plateau may be arranged in approximate order of decreasing durability:

quartzite > quartzose sandstone > chert > limestone
> local gray sandstone > micaceous crystalline > shale

Most variation in the composition of stratified drift may be explained by two factors (Aber, ms, 1978):

1. distance from source areas of different rock types;
2. distance of meltwater transportation.

In any particular area, meltwater transportation is the more important factor. Crystalline exotics range from the most durable to nearly the least durable of the rock types. Thus, the total amount of crystalline exotics in stratified drift does not seem to have been greatly affected by meltwater transportation.

EXOTIC-RICH TILL

The abundance of exotics in till within major through valleys has been known since the work of Holmes (ms and 1952). Holmes hypothesized that strong basal currents existed in the ice sheet (extrusion ice flow) and that these currents carried exotics into the deep through valleys but not onto the uplands. If Holmes' theory of exotic-stone transportation by basal-ice flow is accepted, then certain consequences may be predicted:

1. Extra-Plateau exotics (quartzose sandstone and crystalline rocks) should be most abundant in drift within straight, wide, deep through valleys that open onto the Ontario-Mohawk lowland.
2. Extra-Plateau exotics should be less abundant in drift within narrow, crooked, shallow through valleys that do not extend directly from the Ontario-Mohawk lowland.
3. Extra-Plateau exotics should be least abundant in drift in upland areas and small valleys that have no connections to the through-valley system.

Oneida-Hamilton area.—These predictions arising from Holmes' theory were tested by sampling of till near the northern margin of the Plateau in the Oneida-Hamilton area (fig. 1). Till samples from all ranges of elevations and many topographic situations both in and out of through valleys were analyzed for exotic-pebble content. No correlation between the percentage of extra-Plateau exotics and topographic situation or elevation is discernable (fig. 10). There is a complete overlap in the range of data, with one exception. The exception consists of a single sample from an exposure along state highway 26, 2.4 km east of Eaton. It has an unusually high roundness value of 213, compared to the average till-pebble roundness value of 137 (21/747, $s = 27$) for this area. This sample contains a high percentage of extra-Plateau exotics; it has 15.1 percent, whereas the average value for area till is only 4.6 percent (22/3773, $s = 3.3$ percent). Clearly, this sample is compositionally different from other till in the area. The site of this sample is located in a major through valley, and the rounded exotics may well have been derived from preexisting stratified drift.

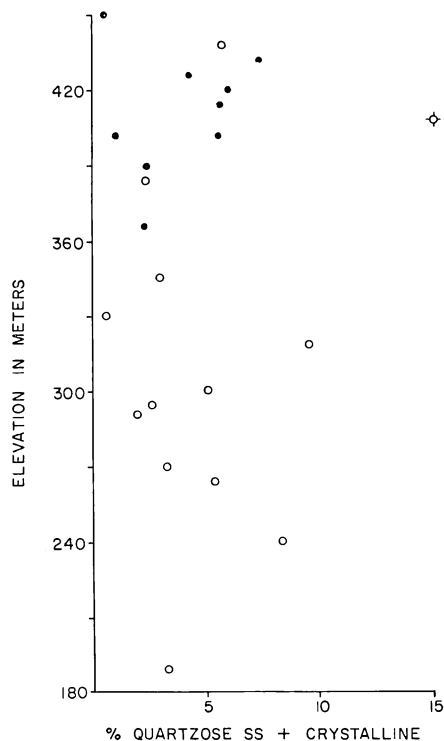


Fig. 10. Plot of composition (13-25 mm size) versus elevation of till samples near the northern margin of the Appalachian Plateau in the Oneida-Hamilton area. Closed dots represent samples from non-through valley locations, and open circles represent samples from through valleys. Sample with an exceptionally high roundness value (213) is starred.

Finger Lakes area.—Careful review of data presented by Holmes on till composition in the Finger Lakes region (fig. 2) reveals that the patterns of exotic-rock distributions are inconsistent with the predictions given here from his theory. Holmes shows that the maximum southern concentration of red and green (quartzose) sandstone exotics occurs in till within the valley that contains Keuka Lake (northwest Hammond-sport quadrangle). This valley does not extend northward to the edge of the Plateau; the two northern branches of the valley lead onto a low upland area north of Keuka Lake. If the predictions from Holmes' theory are valid, then extra-Plateau exotics should be most abundant in drift within the much larger Seneca and Cayuga Lake valleys.

One way to examine differences in drift composition between valleys in southcentral New York is to compare data from valley segments of the Valley Heads moraine. Deposits forming this moraine are of ice-contact origin, both till and stratified drift, and all of about the same age. Therefore, differences in composition between moraine segments in various valleys should reveal differences in ice movement within the valleys. Major valley segments of the moraine were sampled in four areas: three of the areas are in through valleys south of Finger Lakes (Cayuga, Seneca, and Canandaigua), and the fourth area is in a non-through valley at Savona, N. Y. (fig. 11). With the exception of lime-

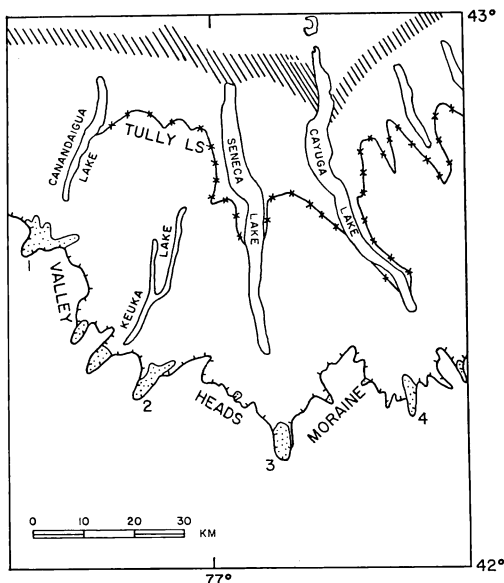


Fig. 11. Map of Finger Lakes region showing the Valley Heads moraine and Tully Limestone. Thick valley segments of the moraine are shown by stipling, and the Onondaga and Helderberg limestones by diagonal lining. Four sampling areas in the moraine are numbered: areas 1, 3, and 4 are in major through valleys, while area 2 is in a much smaller valley at Savona (see table 2). Position of moraine from Denny and Lyford (1963).

TABLE 2

Composition data (13-25 mm size) for major segments of the Valley Heads moraine. Sampling areas (1-4) shown in figure 11; number of samples from each area is shown in parentheses. Mean value for each rock type from each area is shown, as well as the standard deviation(s) about the mean. Note that total exotics are more abundant in areas 3 and 4, whereas extra-Plateau exotics (quartzose ss and crystallines) are more abundant in areas 1 and 2.

		#1 (5)	#2 (6)	#3 (11)	#4 (4)
lime- stone	mean	4.9	3.8	15.0	12.7
	s	1.4	3.2	10.9	11.1
chert	mean	2.6	0.8	1.4	0.7
	s	1.6	0.7	1.2	0.6
qtz ss	mean	4.3	5.5	3.7	3.3
	s	1.3	1.8	2.6	1.2
cryst	mean	2.6	2.1	1.8	2.1
	s	0.7	2.4	1.5	0.9
total exor	mean	14.8	12.1	22.2	18.7
	s	3.3	4.8	15.3	12.3

stone, there do not seem to be great differences in exotic-rock content of the moraine in these four areas; in fact, quartzose sandstone pebbles are more abundant in drift of the non-through valley at Savona than in drift of the through valleys (table 2). Limestone abundance in the moraine is obviously different. There is a high percentage of limestone pebbles in moraine segments south of Seneca and Cayuga Lakes but much less in the areas west of the Seneca Lake valley.

The pattern of limestone abundance in the Valley Heads moraine can be explained by the outcrop position of the Tully Limestone (fig. 11). The Tully Limestone crops out a few kilometers north of the moraine segments in the Cayuga and Seneca Lake valleys. If the dip of the Tully Limestone is projected southward, then its position beneath the axes of these two deep lakes must come quite close to the moraine. East of the Seneca-Cayuga Lakes area, the Tully Limestone becomes shaley, and to the west the unit thins and disappears at Canandaigua Lake (Fisher, Isachsen, and Rickard, 1971). Thus, the abundant limestone pebbles in the Valley Heads moraine south of Cayuga and Seneca Lakes may be due to the proximity of the Tully Limestone. West of the Seneca Lake valley, the Tully Limestone crops out as much as nearly 50 km north of the moraine, and the limestone content of the moraine is considerably less.

Extra-Plateau exotics are more abundant in drift within valleys west of the Seneca Lake valley. Crystalline exotics are more striking in both number and variety in drift of western New York than in areas to the east or south. This information confirms Holmes' finding that there is a general northwest to southeast decrease in the abundance of crystalline exotics in drift of the Appalachian Plateau (fig. 2C). Because the distribution of crystalline exotics does not follow distribution patterns for the other exotic types, Holmes (1952) assumed that the crystalline exotics were largely derived from earlier drift of unknown distribution rather than directly from outcrops in the Canadian Shield. If crystalline exotics were derived from some preexisting drift, then other exotic types should also have been derived from that drift. As will be shown, reworking of exotics from pre-Late Wisconsin drifts probably did occur, and this implies that the distribution of crystalline exotics must be substantially different from that of other exotic types.

Till-stone shape.—If the theory of extrusion ice flow cannot be accepted, then another mechanism must be responsible for producing the abundance of exotic stones in till of through valleys. The clue comes from the nature of the exotic stones themselves. The majority of exotics in exotic-rich till is rounded. This observation was verified quantitatively in the Binghamton-Elmira area by J. Flint (ms, p. 20), who stated, "The upland till contains a large amount of angular material, while valley wall till (exotic-rich) has a noticeably larger proportion of rounded pebbles." At the northern edge of the Plateau near Hamilton, till samples with high roundness values also have a high content of exotics (fig. 10).

Holmes (1960) believed that the roundness of stones in till was produced during glacial transportation; ". . . glacial transportation can and does cause rounding to a high degree if the stone escapes crushing, and that the observed degrees of roundness are chiefly the effects of glacial abrasion." (p. 1653) This does not fit the classic idea of till stones, which are often described as faceted, pentagonal, or "flatiron" shaped (R. F. Flint, 1971). Although Holmes recognized that some stones might have been rounded by an episode of water transportation before incorporation into the glacier load, he believed that this possibility was not important. He concluded that glacially rounded clasts may be recognized, because they retain traces of original concave surfaces much more so than water-rounded stones. In fact, the great majority of pebbles in both ice-contact stratified drift and outwash deposits has concavities, in spite of the fact that they were transported by meltwater streams. Some 79.4 percent (11/655, $s = 10.0$ percent) of all pebbles (except shale) in the Valley Heads moraine at Horseheads have concavities, and 70.0 percent (6/576, $s = 8.1$ percent) of pebbles (except shale) in outwash gravels graded to the moraine have concave surfaces.

Many of the rounded stones in exotic-rich till may have been rounded during an episode of meltwater transportation. The evidence presented in the preceding sections clearly shows that well-sorted strati-

fied drift with rounded pebbles contains abundant exotics. It seems likely that till with rounded stones and many exotics was derived largely from preexisting, exotic-rich, stratified drift. In southern New York and northern Pennsylvania, the fact that exotic-rich till occurs only in major valleys, where preexisting stratified drift might have been located, is strong support for this idea, which was first proposed by Denny (1956).

MECHANISM FOR THE MOVEMENT OF EXOTICS

The movement and concentration of exotic stones in valleys of the Appalachian Plateau during glaciation must be considered a multicyclic phenomenon (Aber, ms, 1978). During each deglaciation stage, durable, exotic rock types were concentrated in stratified drift within valleys by the sorting action of meltwater streams. Once an exotic stone was carried into a valley, it was not likely to have been moved up, out of the valley by later glaciations. Thus with each glaciation, the number of exotic stones left in drift within the main valleys increased. Exotic-rich till and stratified drift should be viewed as products of redeposition during the latest glaciation. Hence like many other glacial deposits, exotic-rich drift is composed largely of redeposited sediments and not freshly eroded bedrock (Gilberg, 1977).

Direct evidence for this mechanism is preserved near Vestal, N. Y. (fig. 1), where exotic-rich gravel of probable Early Wisconsin age is overlain by 20 m of exotic-rich till of Late Wisconsin age (Aber, ms, 1976). The discovery of this Early Wisconsin gravel confirms Denny's (1956) hypothesis that such exotic-rich gravels existed in front of the advancing Late Wisconsin glacier. Exotics are most abundant in the overlying till just above the gravel, suggesting that exotics in the till were reworked from nearby gravels. It is probable that exotic-rich drift in the valleys of southern New York and northernmost Pennsylvania was reworked alternately by glacial ice and meltwater streams several times during the repeated glaciation of the Plateau.

Crystalline exotics are the one exception to this general scheme; they are concentrated in neither exotic-rich till nor stratified drift. The other exotic types were concentrated during episodes of meltwater transportation. However, it seems from study of sequences along the Chenango River valley that crystalline exotics as a group were not greatly affected by meltwater transportation. Thus, while many crystalline exotics might have been reworked from earlier drift, they were not concentrated by glaciofluvial action within major valleys, as were other exotic types.

DISTINCTIVE EXOTIC ROCK TYPES

Crystalline rock types, present in great variety in drift of central New York, are the most distinctive of the different exotics. Quartzites and gneisses comprise the bulk of crystalline types. The general northwest to southeast decrease in crystalline exotics in drift of central New York indicates that most of these exotics were derived from outcrop areas in the Canadian Shield north of Lake Ontario. Although the Adirondack

Mountains could have served as a source for crystalline exotics, few Adirondack-type exotics are present in the Finger Lakes region. Anorthosite, which forms the high peaks of the Adirondacks, is present only rarely in drift of central New York. Another distinctive crystalline exotic which commonly occurs in drift of central New York, is a coarse-grained granite with a Rapakivi texture of zoned, pink feldspar phenocrysts. Several boulders or cobbles of this exotic can usually be found at any large exposure of stratified drift in the Finger Lakes area. This rock type does not occur in the Adirondack area (Fisher, Isachsen, and Rickard, 1971) and presumably comes from the Canadian Shield north of Lake Ontario.

Garnet-bearing gneisses are present in drift throughout the Appalachian Plateau. Exotics of any kind are extremely rare in drift of northeastern Pennsylvania and the Catskill Mountains of New York (Kirkland, ms). Even so, in northeastern Pennsylvania, "A garnetiferous gneiss derived from the Adirondack Mountains of New York State is the most abundant metamorphic erratic." (Sevon, Crowl, and Berg, 1975, p. 38). The abundance and variety of garnet-bearing gneisses is quite striking near the northern margin of the Plateau, just south of the Adirondacks. However, because of a large number of potential source areas, both in the Adirondacks and the Canadian Shield, the use of garnet-bearing gneisses as indicator exotics may require more study. In fact, it may be possible that some garnetiferous gneisses in eastern Pennsylvania south of the Catskill Mountains were actually derived from metamorphic bedrock of New England and eastern New York.

Kirkland (ms) has discovered several isolated crystalline exotics in drift of the Catskill Mountains. All of these exotics ". . . are entirely compatible with a southern Adirondack assemblage." (p. 11) This is the only direct evidence for ice flow from the Adirondack area into the Appalachian Plateau. All other evidence based on the distribution of crystalline exotics, including the northwest to southeast decrease in crystalline exotics, the abundant presence of non-Adirondack types (Rapakivi granite), and the scarcity of anorthosite, indicates ice flow from Canada southward and southeastward over the Lake Ontario basin and onto the Plateau. The presence of a few Adirondack exotics in drift of the Catskills is due to the proximity of the Catskills and southern Adirondacks.

These facts support the contention of Sevon, Crowl, and Berg (1975, p. 49) that the Adirondack Mountains stood as a barrier to ice-sheet movement throughout glaciation, so that ice movement was mainly around rather than over the mountains. In fact, Connally and Sirkin (1971, p. 1003) have concluded that ". . . the Adirondacks were free of continental ice much earlier than had been supposed previously and possibly were ice-free throughout Woodfordian (Late Wisconsin) time." The concept of an "Adirondack outflow center" during the glacial maximum, as proposed by Coates and Kirkland (1974), is not supported in light of this evidence.

CONCLUSIONS

1. The exotic-stone content of stratified drift is dependent on two factors: (1) distance from bedrock source areas of various rock types, and (2) distance of transport in meltwater streams before deposition. In any particular area, the meltwater transport factor is more important; ice-contact deposits generally contain few exotic-rock types, whereas outwash gravels contain abundant exotic-rock types. Exotics are more abundant in stratified drift than in nearby till because of the sorting action that took place in meltwater streams.

2. The concentration of exotics in drift of major valleys is due to the multicyclic reworking of exotic-rich stratified drift within the valleys. The reworking process of alternate transportation by glacial ice and meltwater streams has occurred several times.

3. The distribution of various crystalline exotics in drift of central New York indicates that ice flowed from the Canadian Shield, across the Lake Ontario basin, and southward and southeastward onto the Appalachian Plateau. The concept of an Adirondack outflow center is questioned. Both the Adirondack and Catskill Mountains probably stood as barriers to the southward transport of exotic drift components.

ACKNOWLEDGMENTS

I wish to thank Wakefield Dort, Jr., who critically reviewed this paper and supervised my doctoral research work at the University of Kansas, and Donald Coates, who introduced me to the field area. Ernest Muller offered many helpful criticisms and suggestions for improving this report. Financial support was supplied by two University of Kansas fellowships and by two Grants-in-Aid of Research from Sigma Xi. Topographic maps of much of the field area were supplied by the New York State Geologic Survey and the Pennsylvania Bureau of Topographic and Geologic Survey. Special thanks go to my wife, Susie, who ably assisted with fieldwork during the summer of 1977 and has since rendered much additional help.

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